Overview of XFEL RF Specifications and Comparison to ILC Specs

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Overview

- LLRF Spec for TESLA Linear Collider
- LLRF Spec for the European XFEL
- How to Control Phase to 0.01 deg.
- Comparison Specs ILC – XFEL

Most critical correlated error

	σ_ϕ [deg]	σ_A/A
TTF 1996	1	1e-2
TTF 1998	0.3	2e-3
TESLA	0.2	3e-4
VUV-FEL	0.1	2e-4
X-FEL	0.01	1.7e-4

Beam/RF Parameters for the TESLA Collider Linac

	Collider	FEL
Accelerating gradient E_{acc} [MV/m]	23.4	9.2–23
Injection energy E_i [GeV]	5	2.5
Bunch charge N_e [10^{10}]	2.0	0.63
Bunch spacing Δt_b [ns]	337	93
Bunch length σ_z [μm]	300	25–50
Norm. design emittance ϵ_x, ϵ_y [10^{-6}m]	10, 0.03 (at IP)	1.5 (at undulator)
Norm. emittance at injection ϵ_x, ϵ_y [10^{-6}m]	8, 0.02	0.9
Beam size at injection $\sigma_{x,i}$, $\sigma_{y,i}$ [μm]	320, 16	150
Beam size at linac exit $\sigma_{x,f}$, $\sigma_{y,f}$ [μm]	60, 3	≈35–60
Initial uncorr. energy spread $\sigma_{E,i}/E$ [%]	2.5	0.1
Off-crest RF phase Φ_{RF} [°]	5	0–30
Correlated energy spread δ_{cor} [10^{-4}]	3	10–1
Total spread $\sigma_{E,f}/E$ at linac exit [10^{-4}]	6	10–1.5

Table 3.2.1: *Overview of beam parameters in the main linac.*

Energy Spread as function of Linac Phase

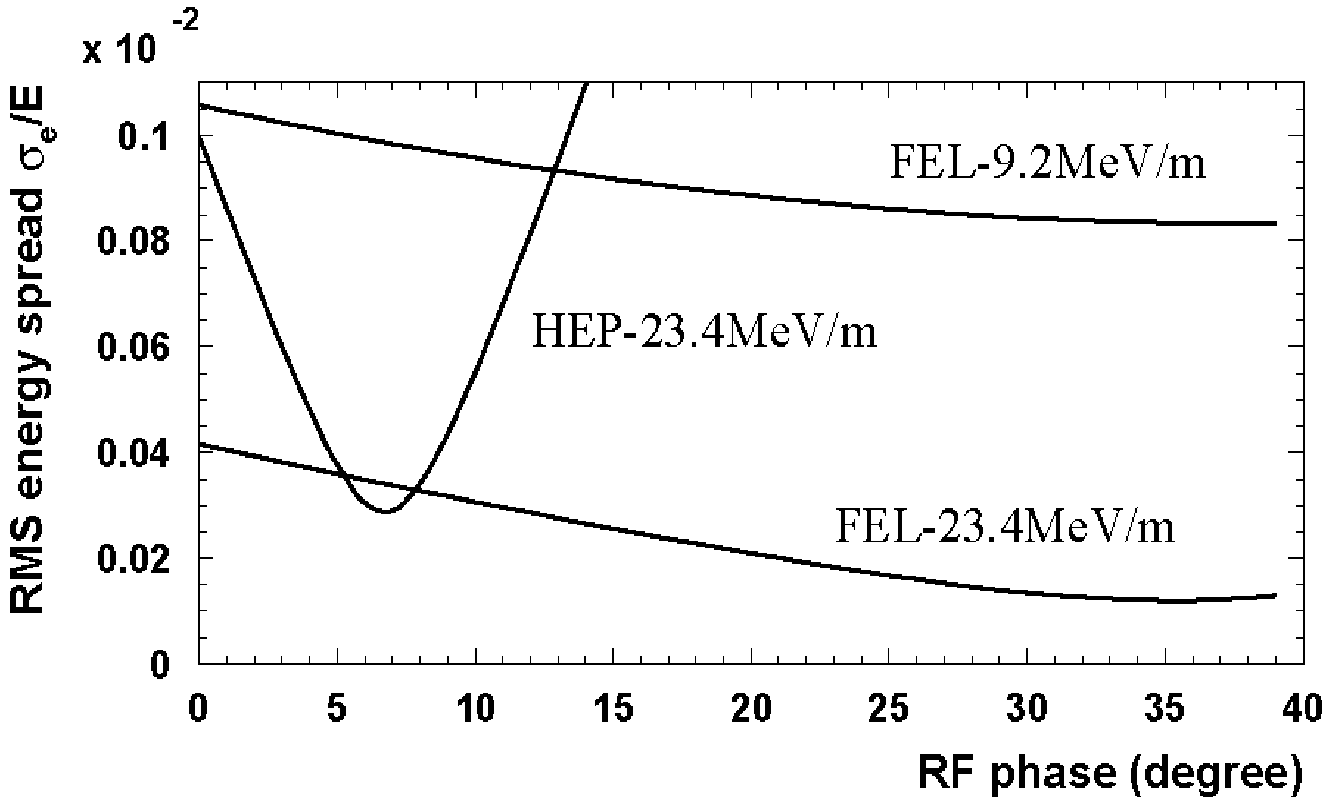
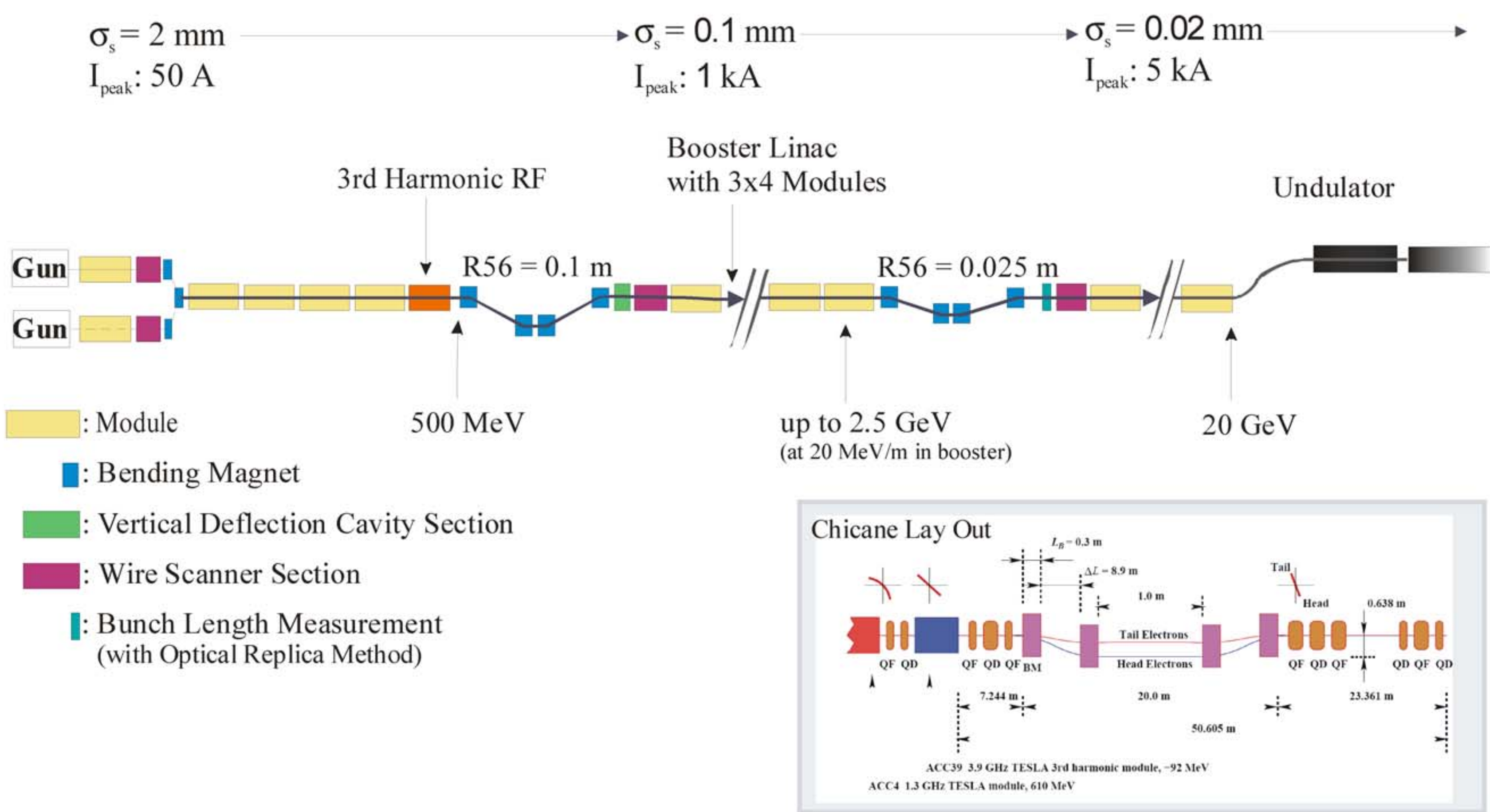


Figure 3.2.3: *Correlated rms energy spread as a function RF-phase for the High Energy Physics (HEP) (E_{acc}=23 MV/m) and Free Electron Laser (FEL) (E_{acc} =9.5–23 MV/m) beams.*

TESLA Linear Collider Linac

- Specification for LLRF Stability derived from Beam properties
  - Energy spread (intra-bunch, bunch-to bunch, long-term)
    - Intra-bunch 5e-4 => desired bunch-to-bunch same order (5e-4) to limit chromatic effects (=> emittance growth)
    - Long term (usually time scale for thermal drift => beam based feedbacks
  - Emittance (can increase as result of chromatic effects)
  - Arrival time (error will reduce luminosity)
- Amplitude and phase stability requirements (assuming error budget is distributed equally on ampl. and phase and -5 deg. off-crest operation for wakefield compensation) :
  - σ_A/A = 3e-4 (corr.) and 5e-3 (uncorr.)
  - σ_ϕ/ϕ = 0.2 deg. (corr) and > 2 deg. (uncorr.)
    - Note: Bunch compressor requirement 0.33 deg. (not including arrival time effects)

Bunch Compressor Configuration for XFEL



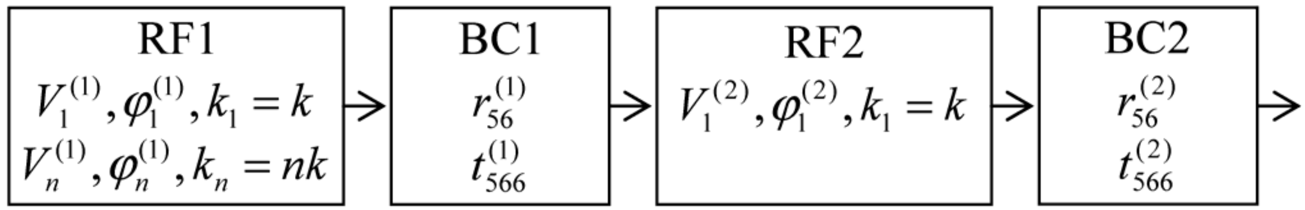
Sensitivity Table for European X-FEL

- Criterion: I_{peak} changes from 5 kA to 5.5 kA (SASE statistical fluctuation: 5-10%)

Can we relax this tolerance?

Linac Phase	0.013	degrees
3rd harmonic Phase	-0.04	degrees
3rd harmonic Amplitude	0.06 (~0.05%)	MV
Magnet Strength 1st Chicane	-0.0005	relative change
Magnet Strength 2nd Chicane	-0.01	"
Beam Parameters		
Charge (I_{peak} = constant)	0.05	relative change
I_{peak} (Charge = constant)	-0.02	"
Charge (Length = constant)	-0.05	"

Schematic of two Stage Bunch Compression



$V_1, V_n, \varphi_1, \varphi_n$ are the voltages and phases for the fundamental mode rf and the nth harmonic of the first compression stage (n=3 for European XFEL, n=4 for LCLS)

V_1 and V_n are later on replaced by normalized amplitudes a_1 and a_n.

Jitter Sensitivity

Error sensitivity of compression factor *C* with respect to phase (or amplitude) offset *x:*

$$\frac{1}{C_0}\frac{\partial C}{\partial x} = A\frac{\partial p}{\partial x} + B\frac{\partial p'}{\partial x}$$

$$p = p(s_a, x)$$

$$\partial p'/\partial x = \partial^2 p/\partial x \partial s_a$$

$$A = -2(C_0 - 1)t_{566}/r_{56}$$

$$B = -C_0 r_{56}$$

Example: For phase jitter of the fundamental mode rf (first stage) $(\varphi_1 = \varphi_{1\,\text{design}} + x)$

$$p(s_a, x) = a_1\cos(k\ s_a + \varphi_1 + x) + a_n\cos(nk\ s_a + \varphi_n)$$

And the bunch compression factor sensitivity is

$$\frac{1}{C_0}\frac{\partial C}{\partial x} = -a_1\left(A\sin\varphi_i + Bk_i\cos\varphi_i\right)$$

Cancellation possible?

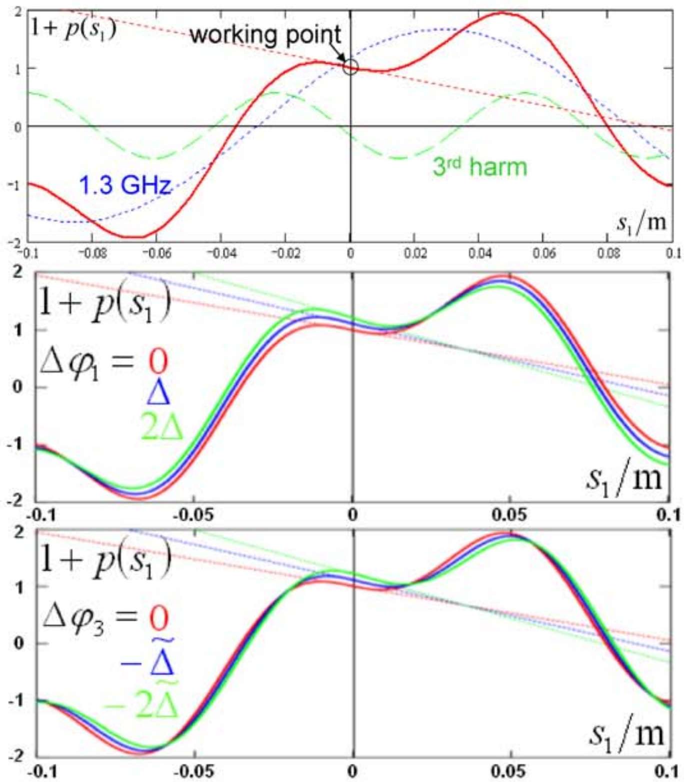
Footnote: 2-stage system in the case of E-XFEL very similar to 1st stage:

$$\frac{\partial C^{(1+2)}}{C_0^{(1+2)}\partial x} = \frac{C_0^{(1+2)}}{C_0^{(1)}\widetilde{C}_0^{(2)}}\left\{\frac{\partial C^{(1)}}{C_0^{(1)}\partial x}\right\} \cancel{- C_0^{(1+2)} r_{56}^{(2)} u \frac{\partial p'^{(1)}}{\partial x}}$$

small for the E-XFEL

Phase Jitter Compensation

Impossible with a single frequency system, but for the combination of fundamental mode and higher harmonic rf systems a working point can be found…



…where for increased beam energy due to phase jitter, chirp increases in strength:

→ effectively reduced R56 of magnet chicane is compensated by the stronger chirp

RF Multi Knobs

Amplitude (normalized) and phase of the fundamental mode rf (a_1,φ_1) and of the higher harmonic rf (a_n,φ_n) are combined to set up four 'knobs':

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & -k & 0 & -(nk) \\ -k^2 & 0 & -(nk)^2 & 0 \\ 0 & k^3 & 0 & (nk)^3 \end{bmatrix} \cdot \begin{bmatrix} a_1\cos\varphi_1 \\ a_1\sin\varphi_1 \\ a_n\cos\varphi_n \\ a_n\sin\varphi_n \end{bmatrix} = \begin{bmatrix} 1 \\ p_0'^{(1)} \\ p_0''^{(1)} \\ p_0'''^{(1)} \end{bmatrix}$$

Beam energy (normalized)

Chirp

2nd and 3rd derivatives of particle momentum deviations

Impact on final longitudinal bunch shape weaker, can be used as a relatively free parameter to reduce rf phase tolerances

RF Phase Jitter Sensitivity Optimization Scenarios

Let‘s pick this one

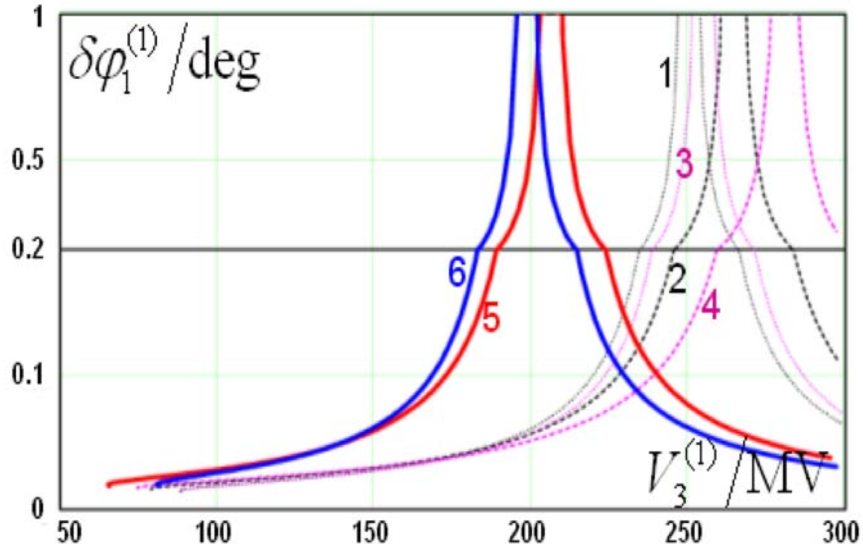
Scanned p''' for different scenarios:

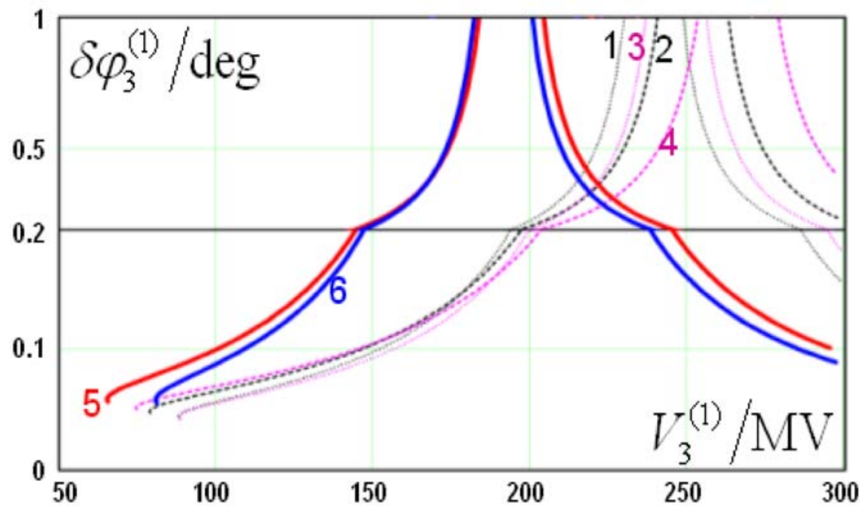
	1	2	3	4	5	6
$E_0^{(1)}/\mathrm{MeV}$	500	500	500	500	**400**	**400**
$C^{(1)}$	20	14	20	14	**14**	**14**
$r_{56}^{(1)}/\mathrm{mm}$	84.4	101.4	82.3	109.3	**89.1**	**68.4**
$\varphi_1^{(2)}/\mathrm{deg}$	0	0	20	20	**20**	**20**
$r_{56}^{(2)}/\mathrm{mm}$	19.2	19.0	29	29.3	**29.3**	**23.5**

Used 1D tracking code which includes:

- wakefields
- non-linearities of rf and magnet chicanes
- longitudinal space charge

RF Phase Sensitivities





The phase and amplitude offsets which are plotted on the vertical scale cause a change of the final peak current of 10%.

3rd harmonic rf voltage plotted on the horizontal axis; it scales with p'''

Conclusion of Sensitivity Studies

- The phase jitter sensitivity of the European XFEL bunch compression system can be reduced by more than an order of magnitude if the amplitudes and phases of the fundamental mode rf and the higher harmonic rf system are correctly chosen to provide phase jitter compensation.

- The 3rd harmonic system has to be operated with an amplitude of 200-250 MV, more than twice the minimum value necessary to compensate the non-linearities of the fundamental mode rf and the magnet chicanes.

  At that working point, phase jitter tolerances are of the order of a degree for both rf systems, compared to a few hundredth of a degree in the previous design. Amplitude jitter tolerances are $1.5 \cdot 10^{-4}$ for the 3rd harmonic rf and $3 \cdot 10^{-4}$ for the fundamental mode rf.

σ_ϕ [deg]	σ_A/A	$\Delta I/I$ %	σ_T fs	Comment
0.005 0.01	6.0e-5 1.7-4	-10 “	30 60	Original bunch comp. parameters
0.01 0.1 1.0	1.7e-4 1.7e-4 1.7e-4	-10 “ “	90 400 4000	With phase jitter compensation $V_3^{(1)}$=200MV

Error Budget for LLRF Control

- Different RF Systems have different requirements for rf stability*
  - Photokathode Laser
  - RF Gun
  - Cavities before BC 1
  - Cavities before BC 2
  - Cavities in main linac
  - Pump probe laser
  - Beam diagnostics

Note: Phase stability is usually meas. with respect to the Master Oscillator

- Contribution to phase noise an drifts
  1. Reference oscillator (close in phase noise)
  2. PLLs generating different frequencies
  3. Distribution amplifiers
  4. Coaxial or fiber distribution system
  5. Local distribution
  6. Local LO-generation
  7. Clock jitter for digital IQ detection
  8. Downconverters

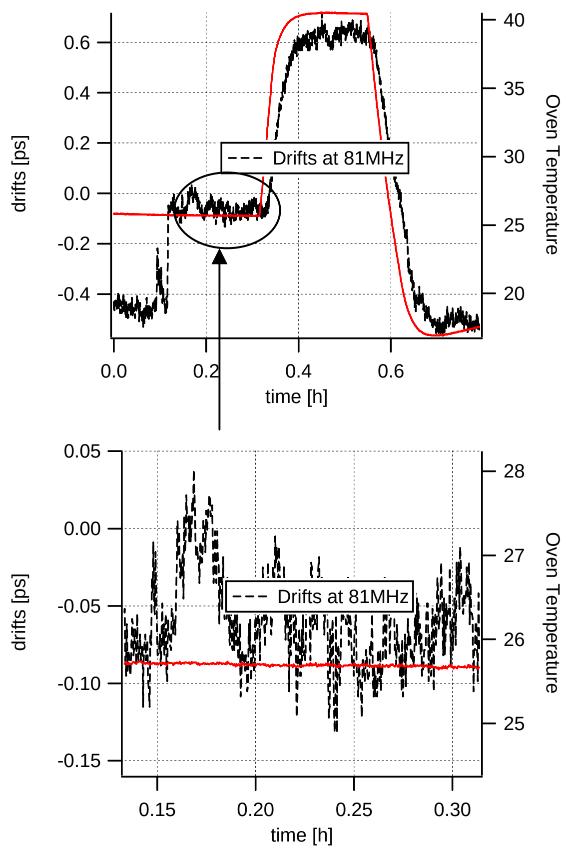
  Note: Fiber Master Oscillator could help to reduce drift components 2.-7. to about 10 fs and reduce integrated phasenoise >10 kHz to a few femtoseconds. Remaining drift of the order of 100 fs / deg. C (Need good temp. stabilization for 10 fs).

Typical Phasenoise and Drifts of Components

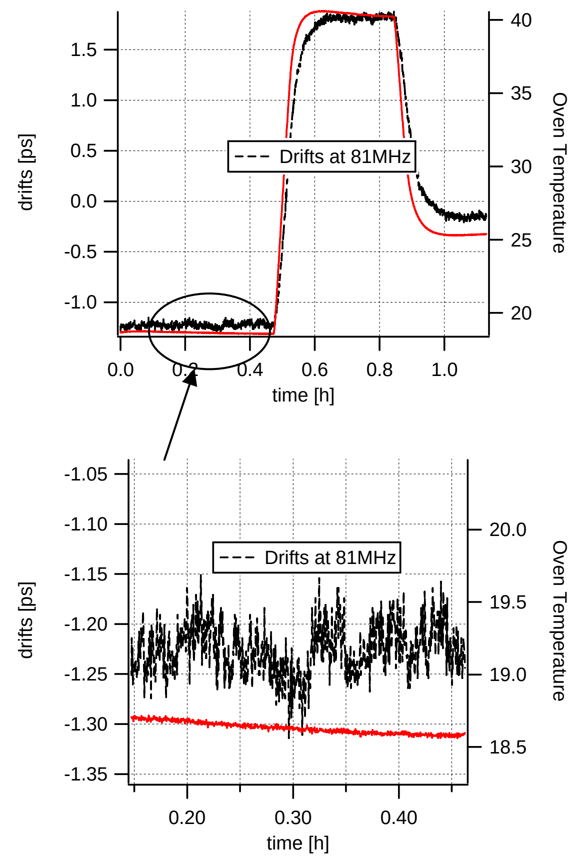
- Phase detectors:
  - 0.1 – 1 ps / deg. C
  - integrated phase noise : ~10 fs (10kHz-1 MHz)
- Phase stable coaxial cables:
  - 1-3 ppm /deg. C
  - some cables quite sensitive to microphonics
- Oscillators : 70 fs (10 Hz – 10 MHz)
- Amplifiers:
  - 0.1 – 1 ps / deg.
  - Ampl. noise > phase noise (PS stability !)

Detectors (comparison long and short cable)

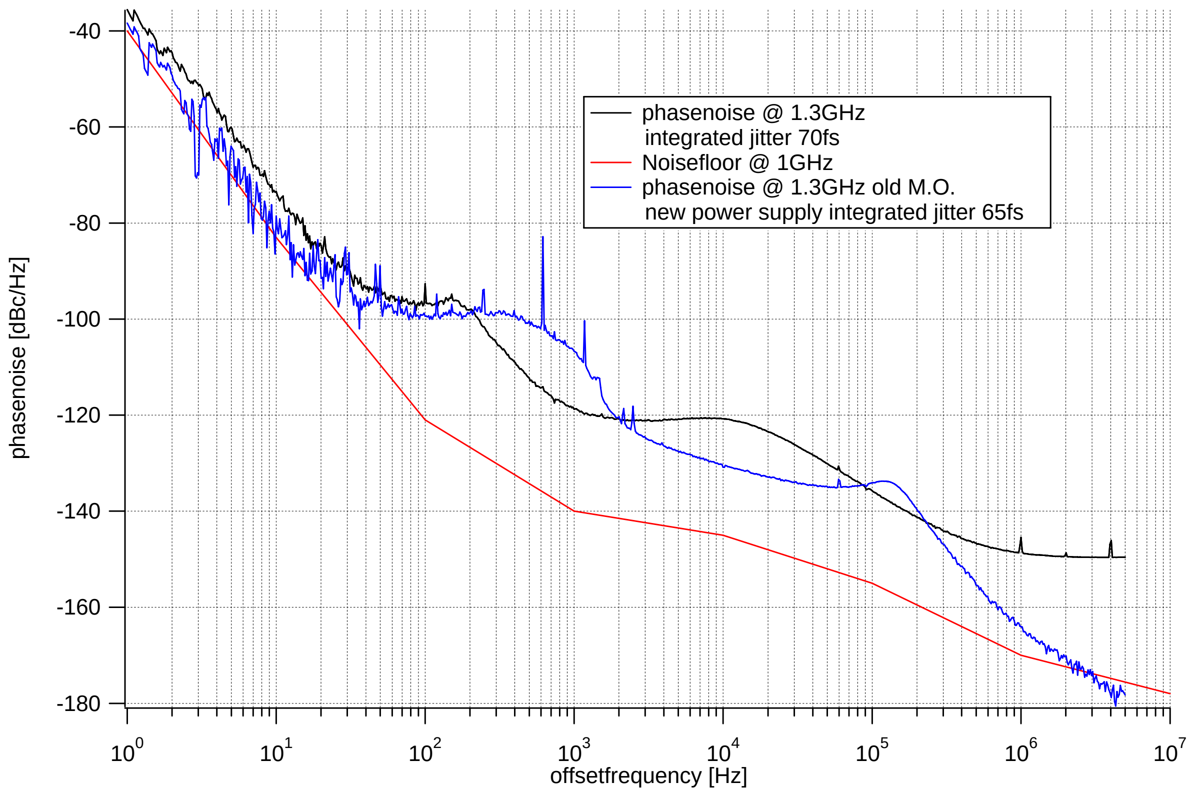
Long cable after splitter



Short cable after splitter



Phase Noise different outputs (1.3GHz)



Expected Performance

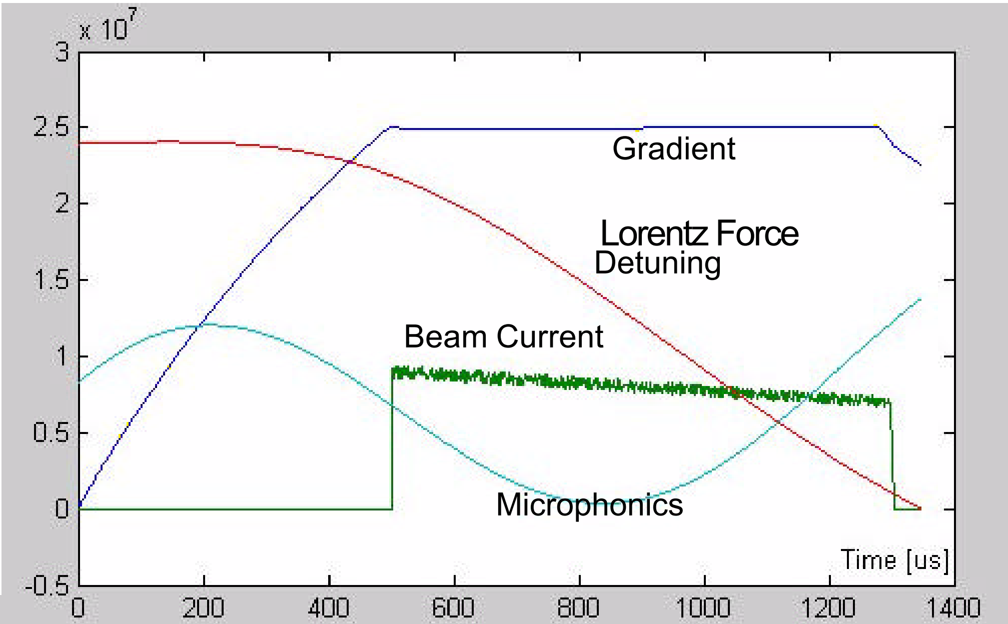
- **LLRF System will be able provide (rough guess)**
  - Short term (< 1 s) stability of 0.01 deg.
  - Medium term (1-100 s) of 0.03 deg.
  - Long term (100 – 1000s) of 0.1-0.5 deg.stability
- **Improvement of long term stability to 10 fs only possible with**
  - Optical master oscillator and distribution
  - Beam based feedbacks

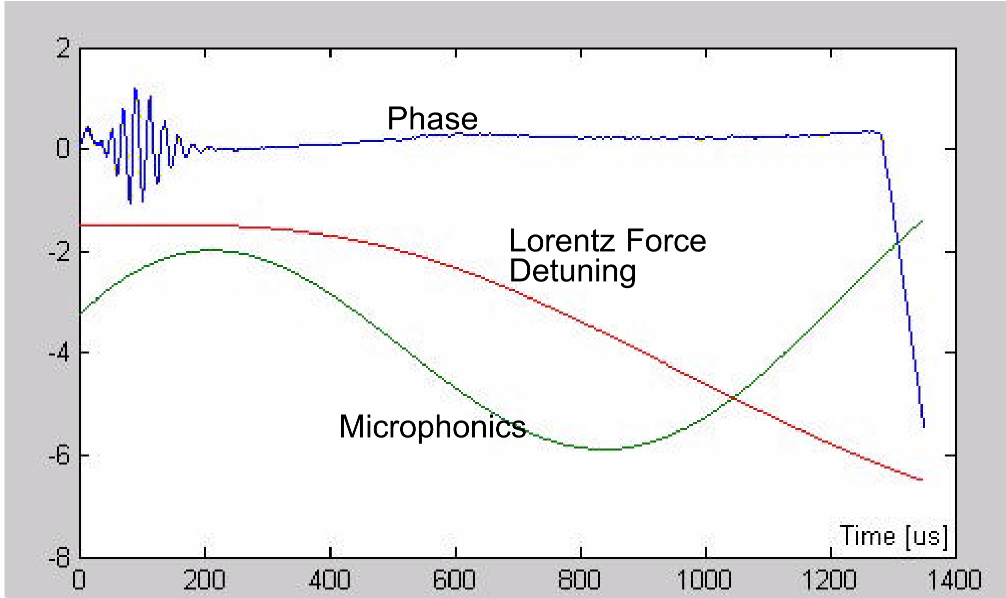
Achieving 0.01 deg. Phase Stability

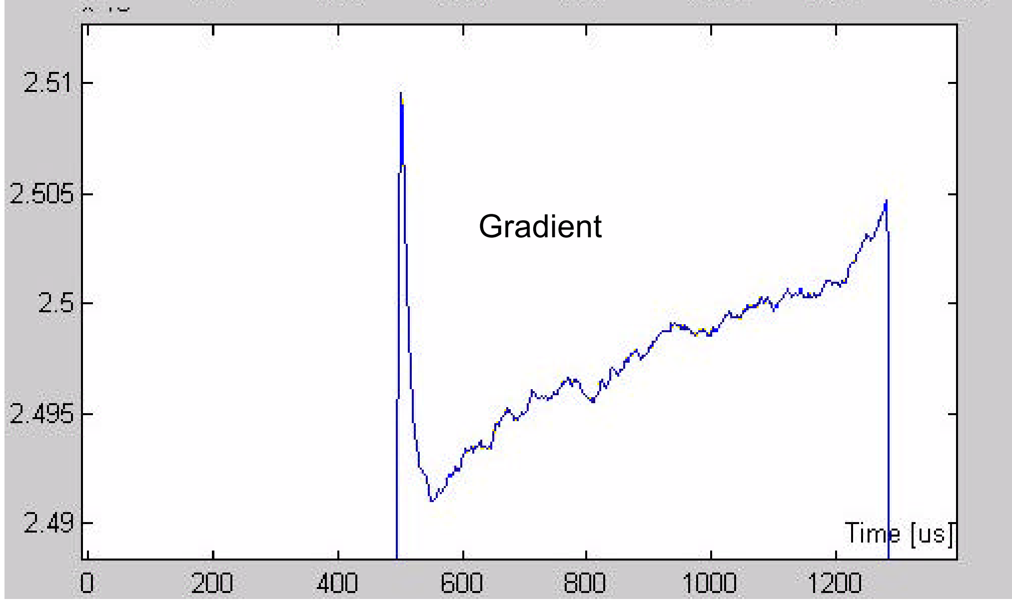
- Short term (within in 1 ms pulse)
- medium term (pulse to pulse, several seconds)
- long term (thermal time scale, minutes to hours)

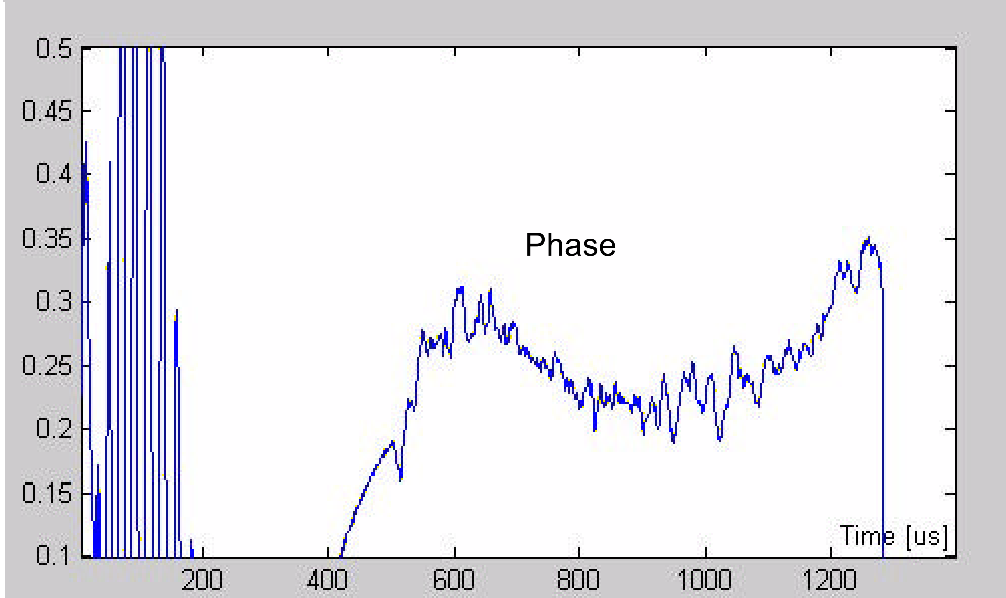
- Sources of cavity field perturbations
  - Lorentz force detuning
  - Microphonics
  - Beam loading
  - other (electronic noise in field detectors, phase noise and drifts of phase reference, ripple of klystron power supply, etc.)

RF Regulation TESLA Cavity (Simulation)

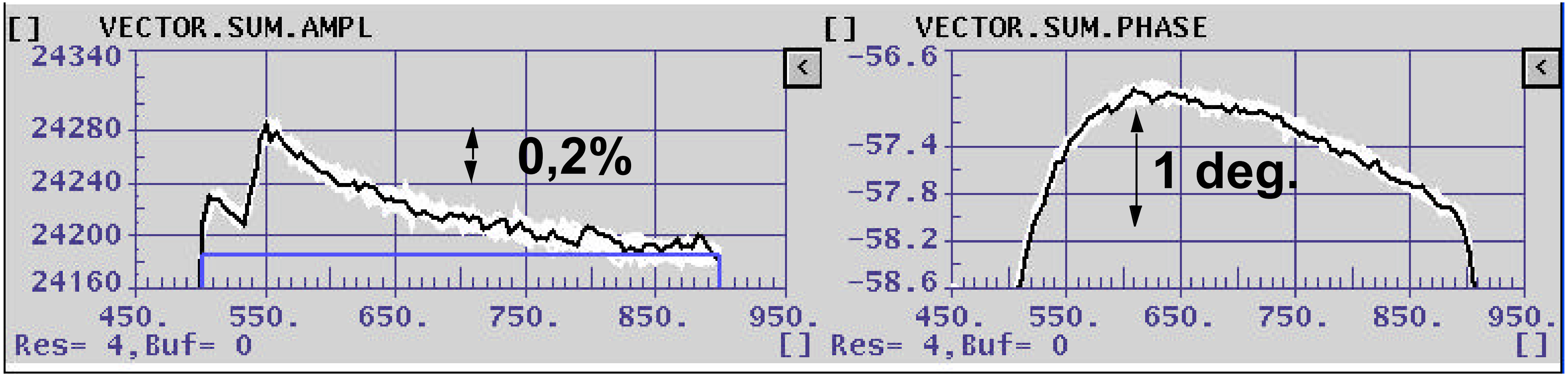


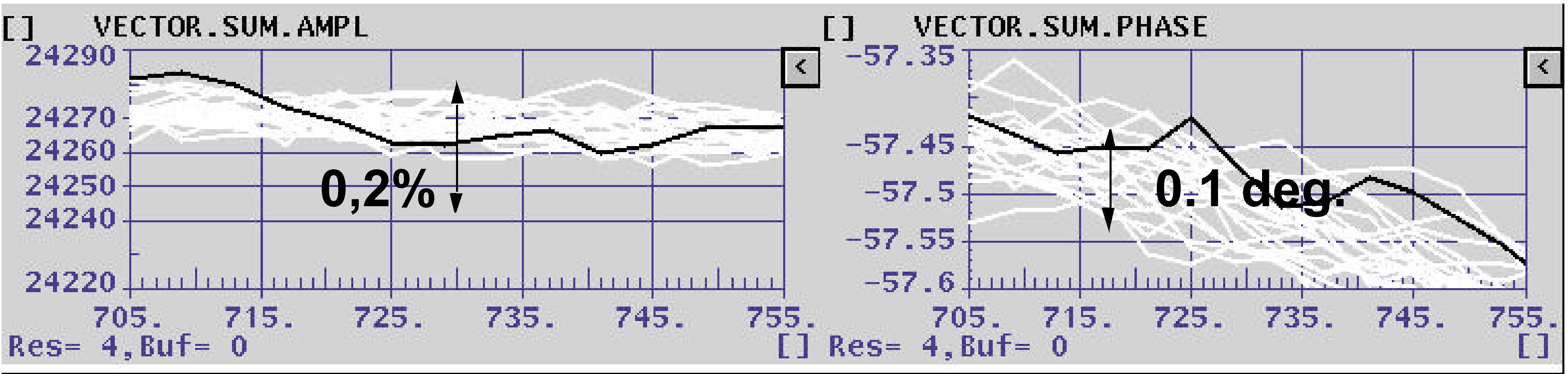




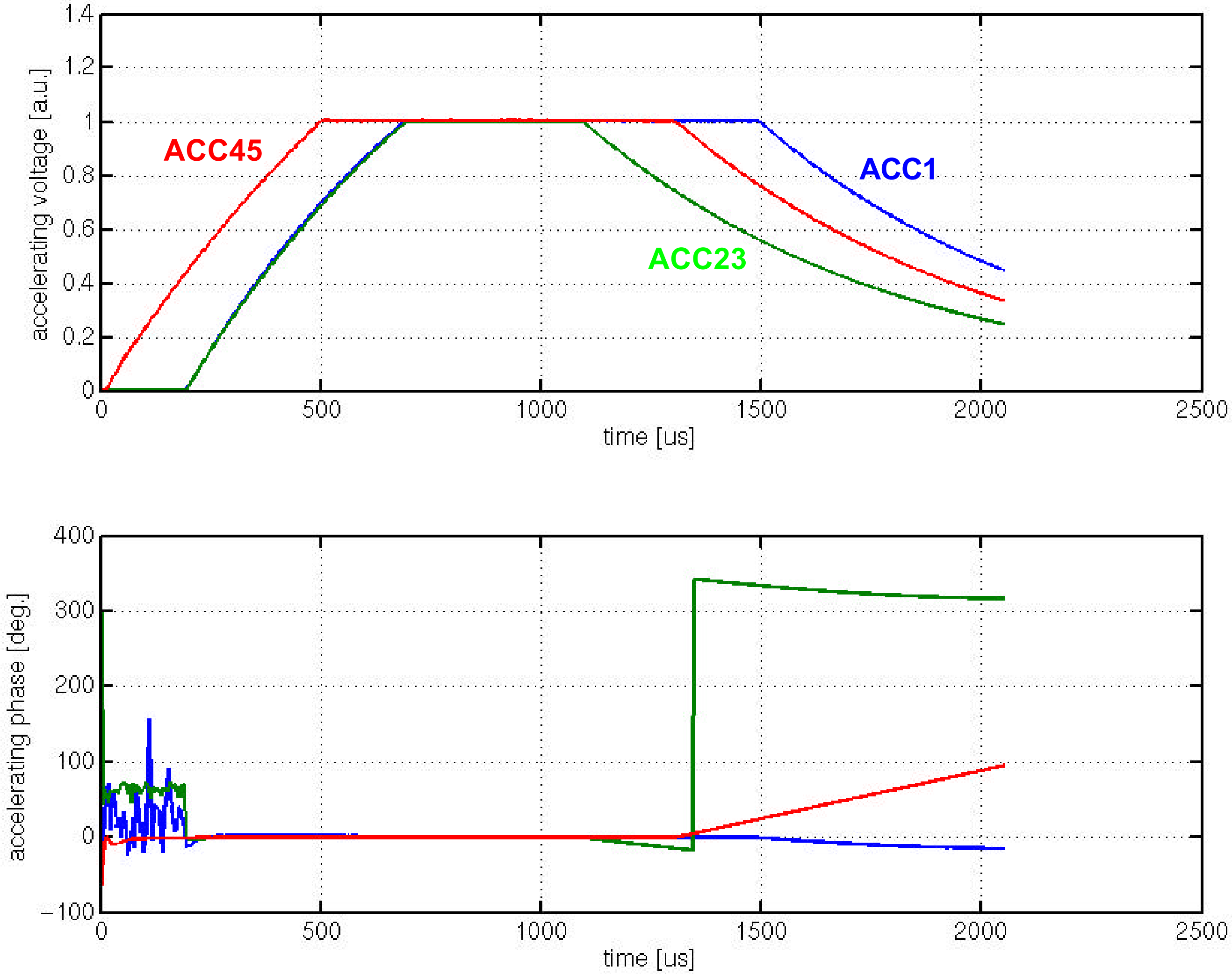


Measured Stability in ACC 2+3

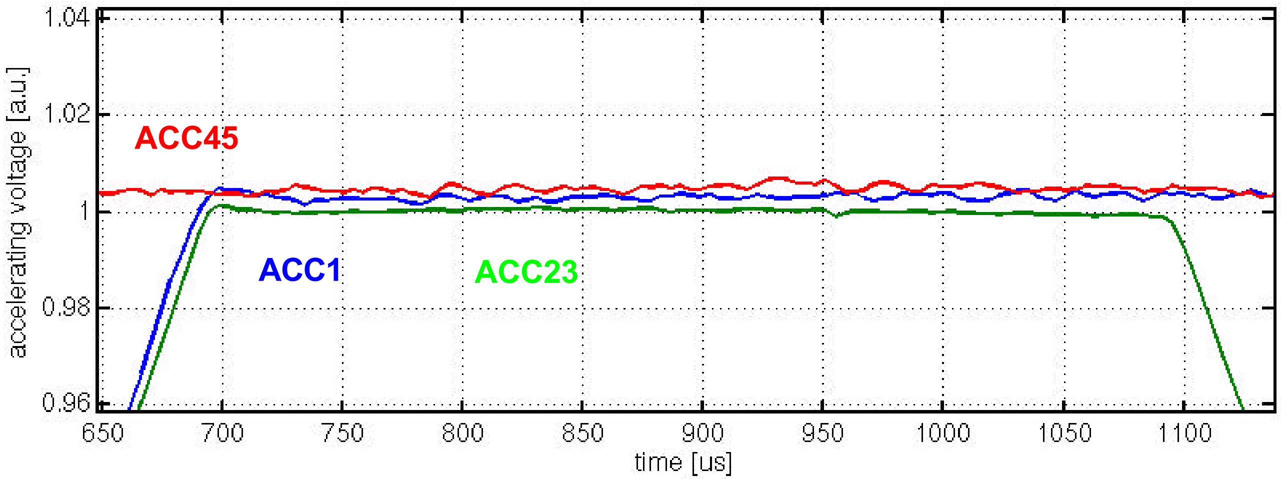


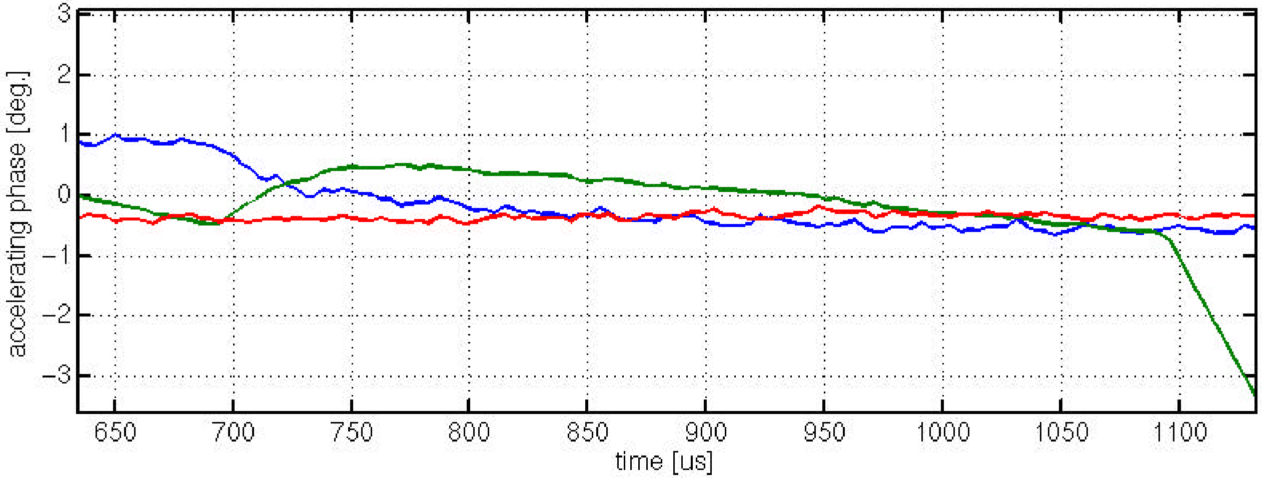


Field Regulation at VUV-FEL

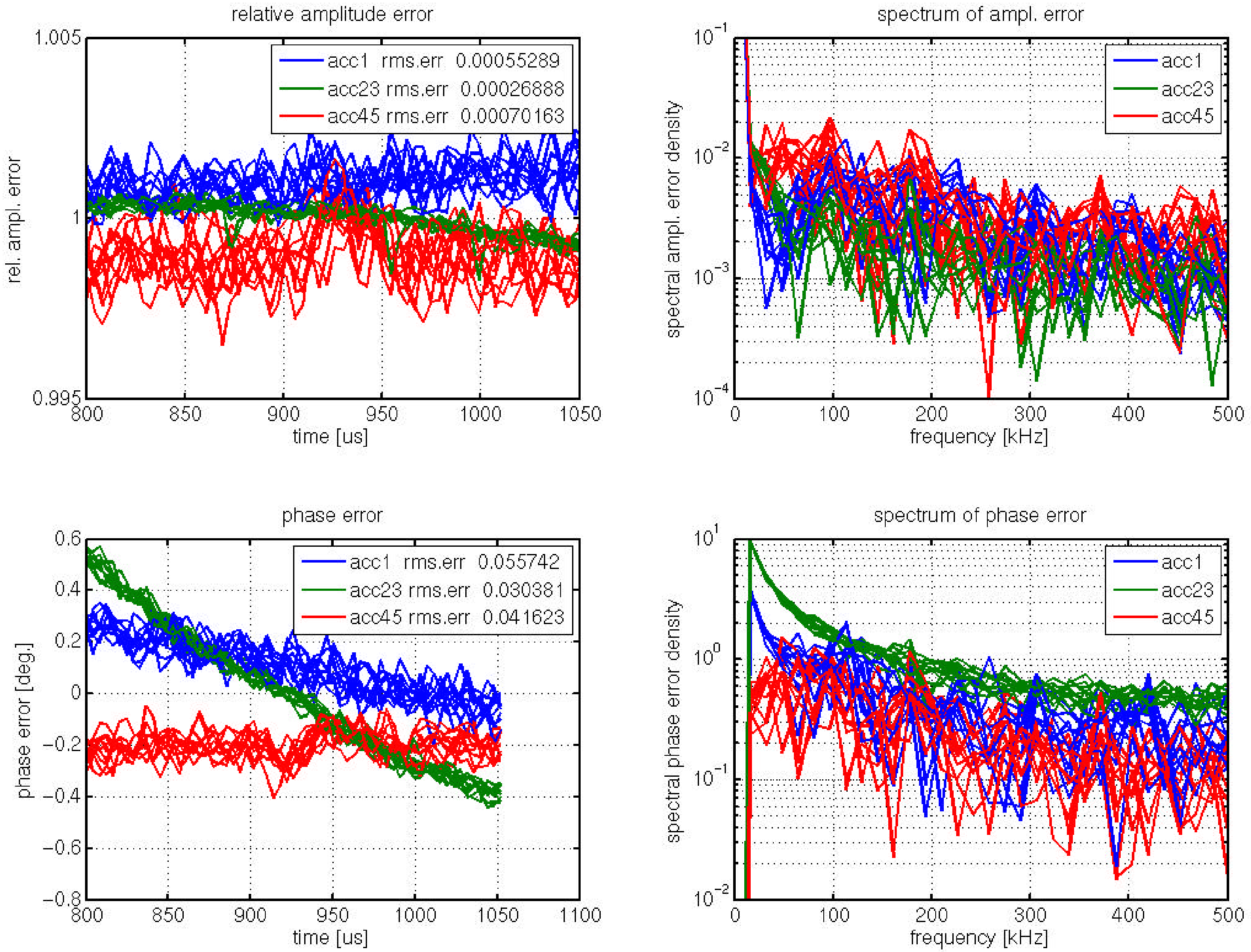


Field Regulation at the VUV-FEL

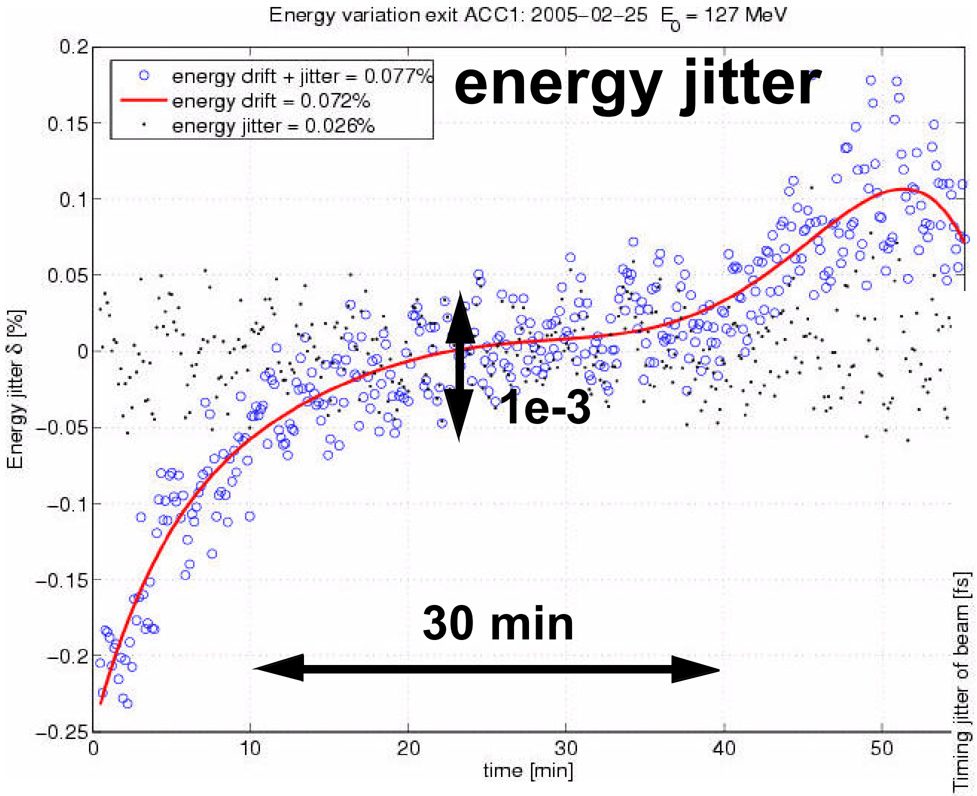


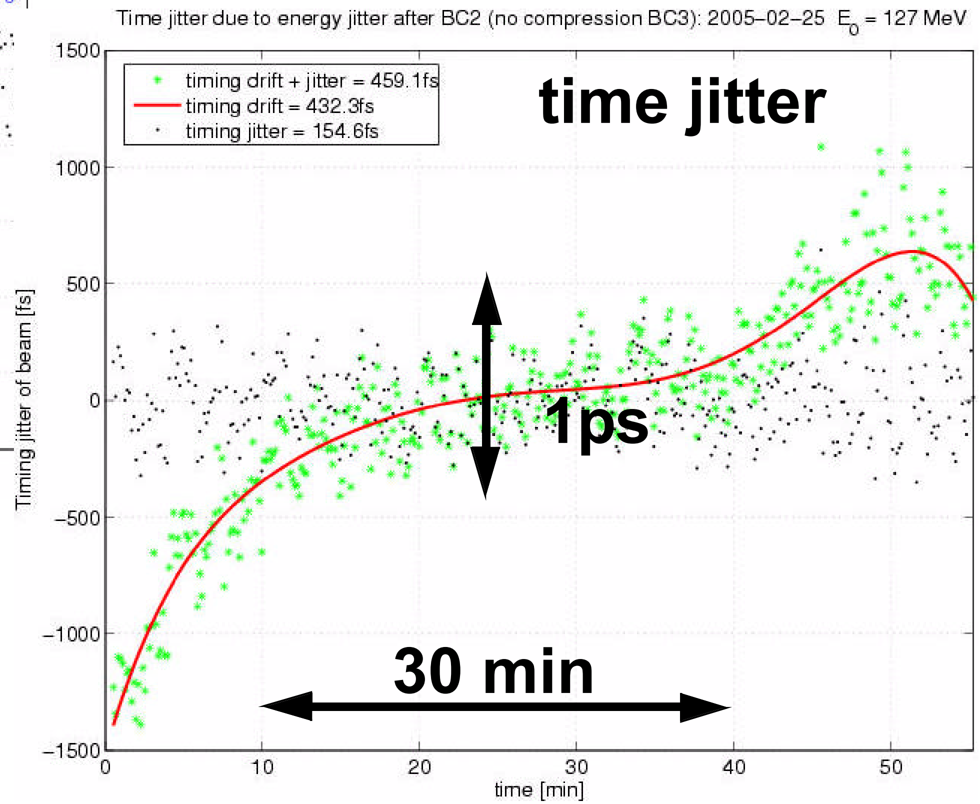


Field Regulation at VUV-FEL

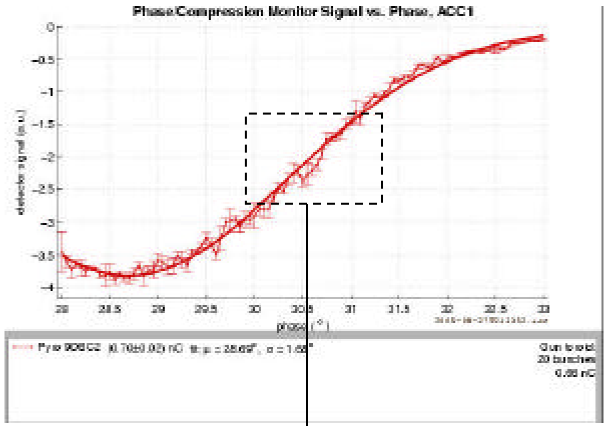


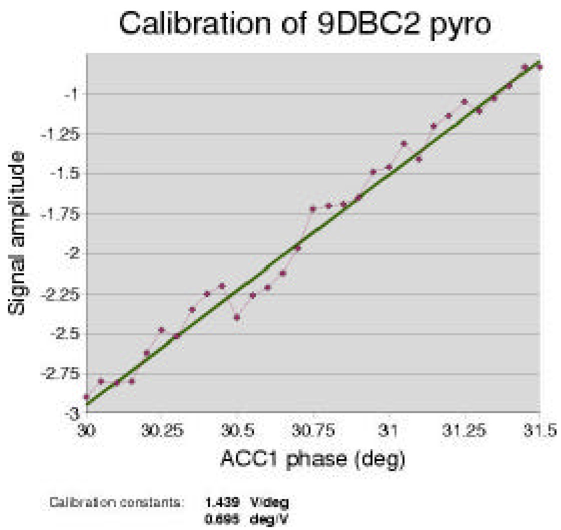
Drift ACC1 (cryomodule before BC) at TTF

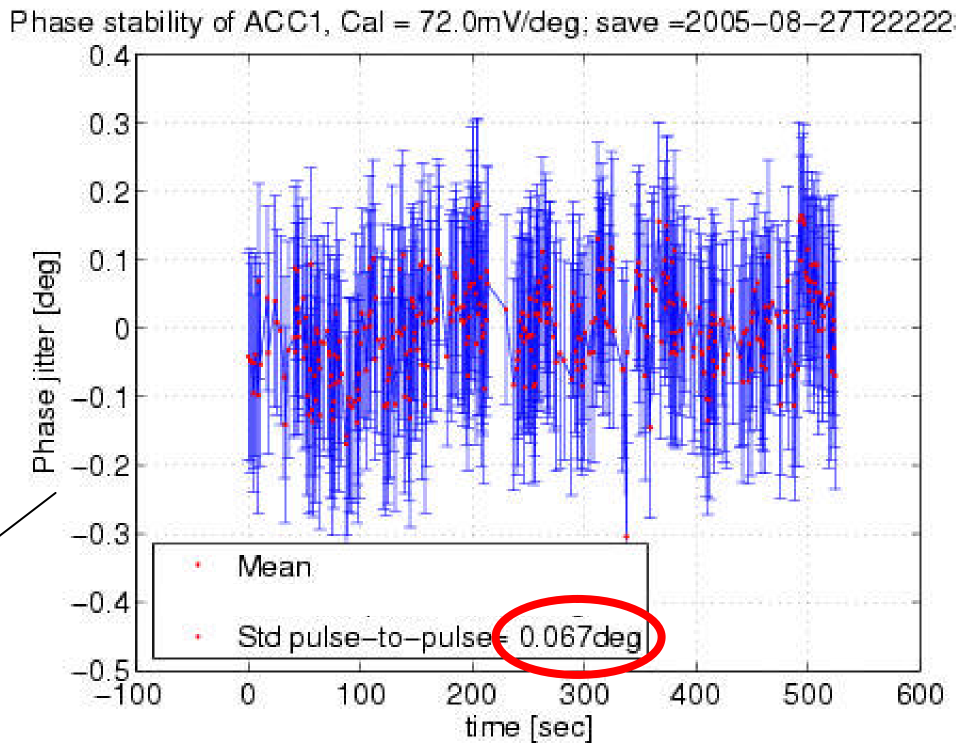




Phase stability with pyro-detector



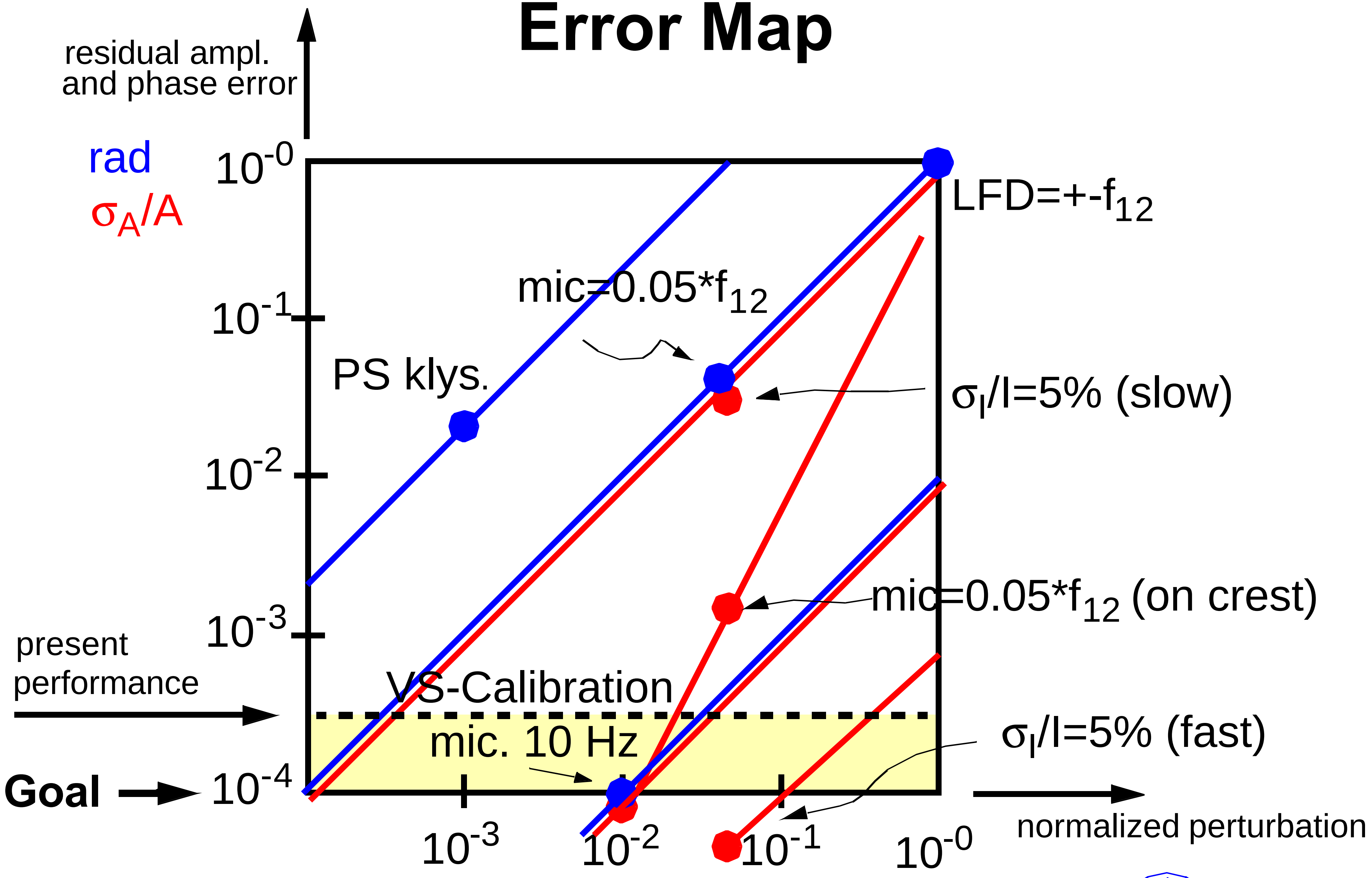




But! This is the phase stability between the beam arrival into the acceleration module relative to the RF phase!!!

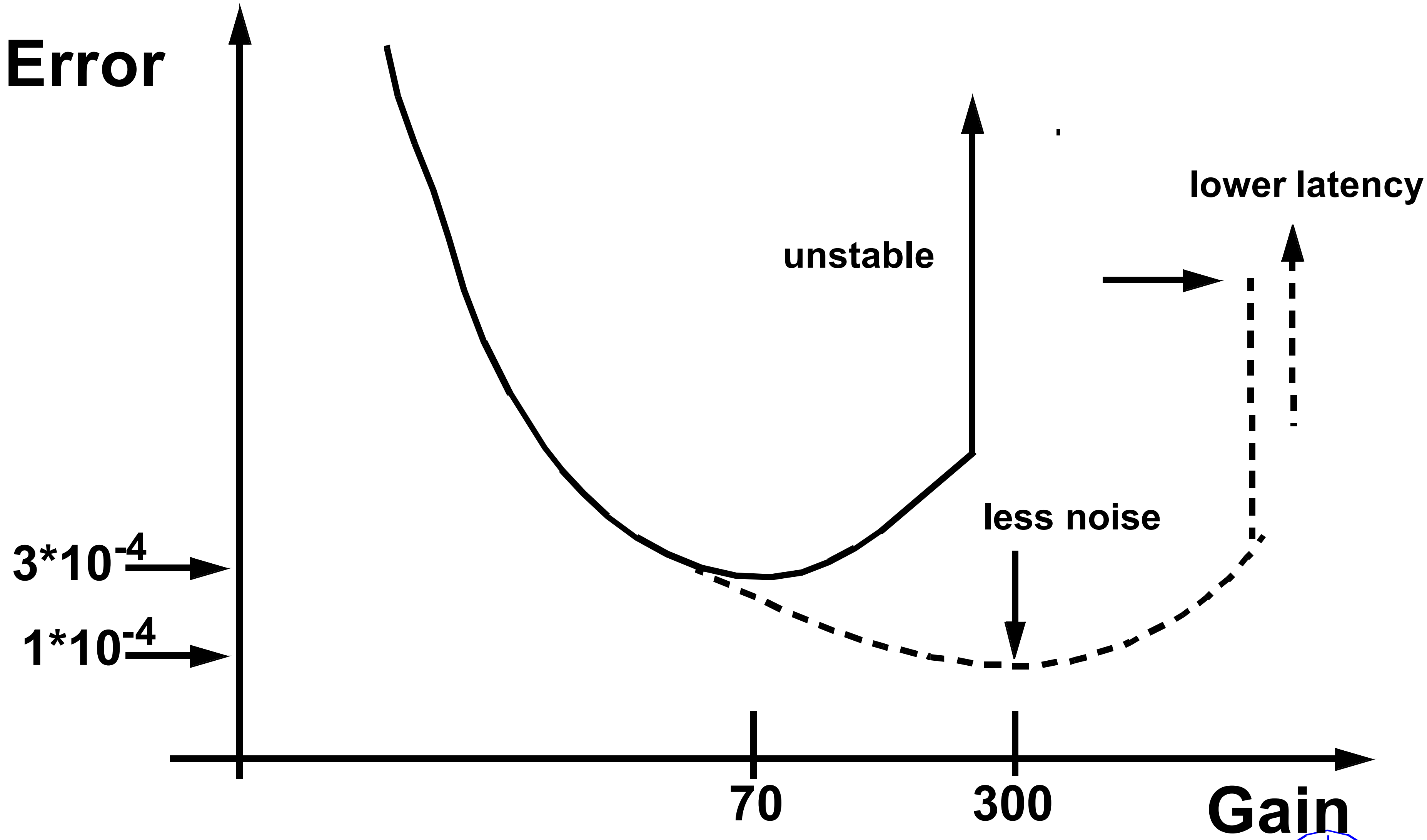
=> Major contribution is likely from laser

Error Map



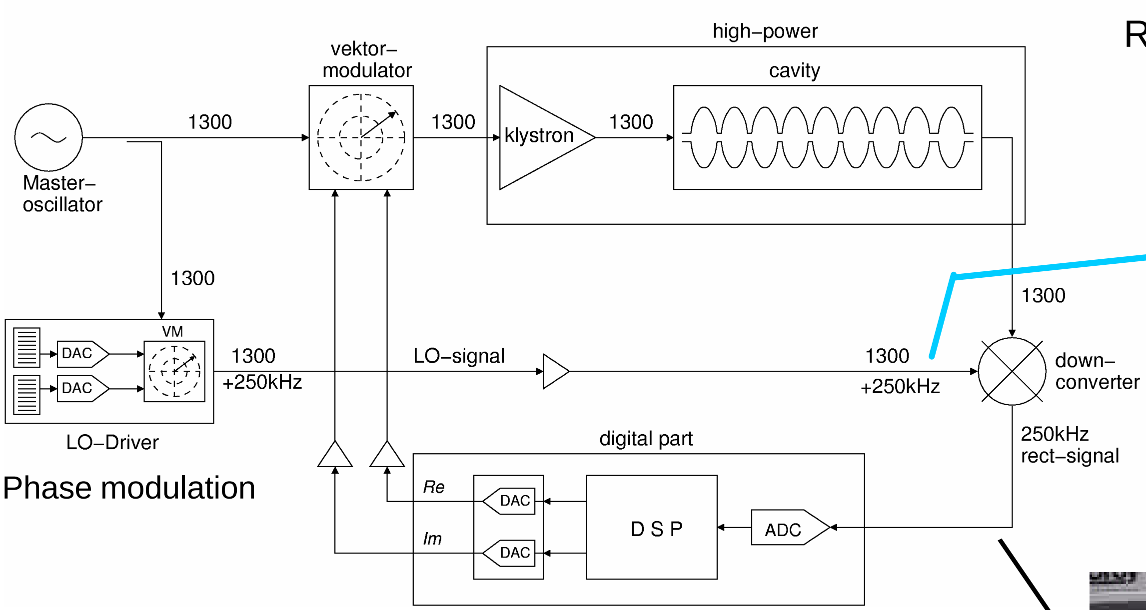
residual ampl.
and phase error
rad
σ_A/A
10^{-0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
present
performance
Goal
LFD=+-f_{12}
mic=0.05*f_{12}
PS klys.
σ_I/I=5% (slow)
mic=0.05*f_{12} (on crest)
VS-Calibration
mic. 10 Hz
σ_I/I=5% (fast)
10^{-3}
10^{-2}
10^{-1}
10^{-0}
normalized perturbation

Improving Cavity Field Regulation



Noise characterization of the LLRF System (TTF2)

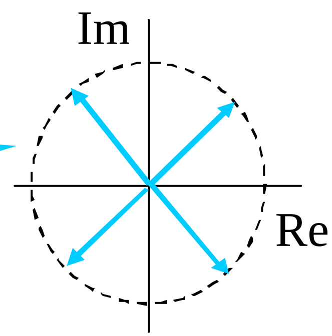
- **RF digital feedback system (TTF2) :**

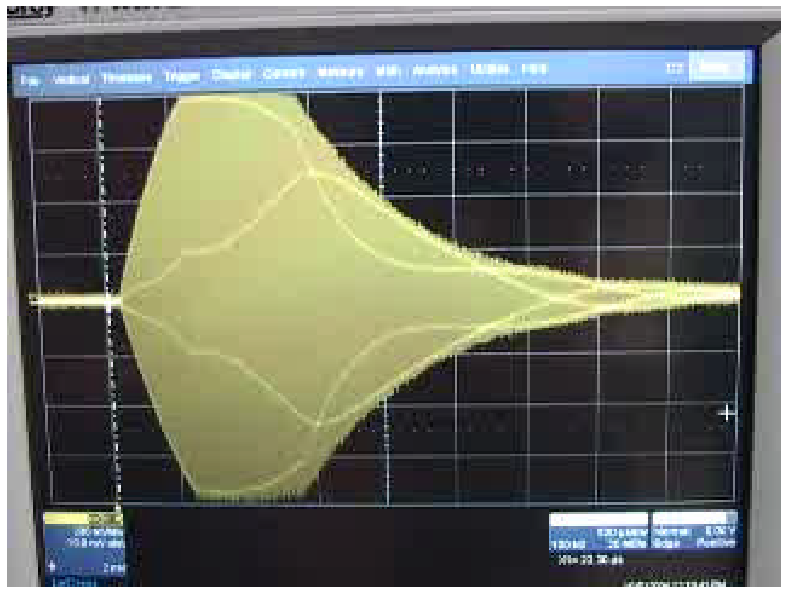


Phase modulation

- **+I,-I,+Q,-Q detection scheme :**

Rotation of the LO-signal in four 90° steps





Bandwidth for transforming 250kHz squared pulses :

$$Df \approx 10MHz$$

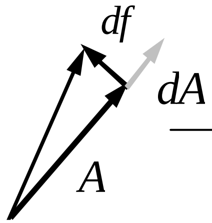
Required regulation bandwidth only :

$$Df \approx 1MHz$$

- **Stability requirements on phase and amplitude of the cavity field vector :**

Amplitude stability : and linearity $\frac{dA}{A} < 10^{-4}$

Phase stability : $df < 0.01°$



$dU_{XFEL} < 100\,\mu V$

(normalized to A=1V)

- **Noise measurement at input of an ADC :**

$$dU_{TTF2} \approx 1.0mV = 10 \times dU_{XFEL}$$

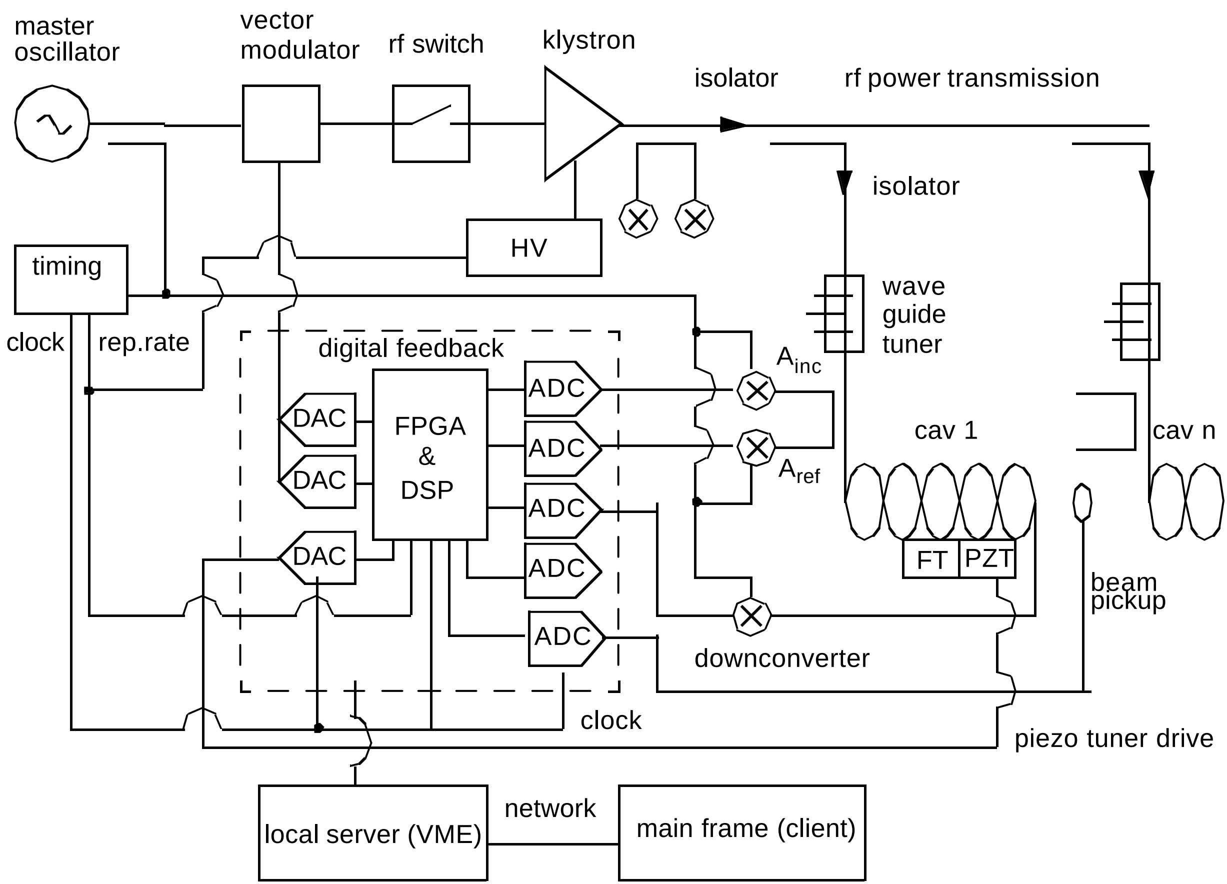
rms-voltage noise :

$$dU = \sqrt{\int_{Df} S_U(f)df} \approx \sqrt{S_U}\sqrt{Df}$$

+ *Reduce the measuring bandwidth*
+ *Low-noise design*
+ *Averaging, switched low-pass!*
- *Correlation methods*

Superposition of all noise contributions :

$$\sqrt{dU_{DWC}^2 + dU_{IQ}^2 + dU_{MO}^2 + dU_{extern}^2 + \ldots} < 100\mu V$$


master
oscillator
vector
modulator
rf switch
klystron
isolator
rf power transmission
isolator
HV
timing
wave
guide
tuner
clock
rep.rate
digital feedback
A_{inc}
ADC
DAC
FPGA
&
DSP
ADC
cav 1
cav n
DAC
ADC
A_{ref}
ADC
DAC
FT
PZT
ADC
beam
pickup
ADC
downconverter
clock
piezo tuner drive
network
local server (VME)
main frame (client)